# Combination of precise GNSS orbit and clocks in a multi-constellation, multi-frequency environment

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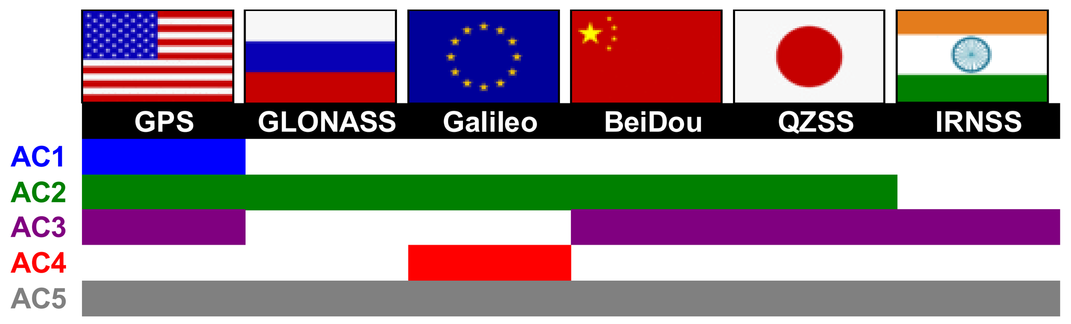
## Introduction

The International GNSS Service (IGS, Dow et al. 2009) is well established as a scientific reference for GPS data processing since more than 20 years. The observations from a global tracking network are processed by a number of Analysis Centers (AC's, typically around ten nowadays) and combined to the official IGS products by the Analysis Center Coordinator (ACC) using an algorithm described by Beutler et al. (1995).

Some of the AC's have extended their activities to GLONASS, the Russian counterpart to GPS by a rigorously combined GPS and GLONASS solution. At the same time, the combination within the IGS takes place in two fully independent chains for GPS and GLONASS.

Extrapolating this current situation by the current development in the frame of IGS-MGEX (multi-GNSS experiment, Montenbruck et al. 2014 ) we will be faced in the future with inhomogeneous contributions by the different IGS AC's:




*(hypothetical scenario on the selection of constellations by IGS AC's)*

### Emerging questions:

What is the optimal combination strategy in order to
- keep the internal consistency between the systems from the contributing solutions into the combined products?
- obtain the optimal quality for the combined orbits of all satellites considering that the quality of the orbits from the different constellations may vary.

With the modernization programs of the established Global Navigation Satellite Systems (GNSS) and the new systems under construction the manifold of frequencies and signals will significantly increase. This development is accomplished by an even more dramatic increase of signal tracking techniques indicated, e.g, in the RINEX3 format description:

| System | Block, type | Frequency | Signal tracking (according to RINEX3) |
|---|---|---|---|
| GPS | IIA, IIR-A/B | L1, | C1C, C1S, C1L, C1X, C1P, C1W, C1Y, C1M |
| | | L2 | C2C, C2D, C2P, C2W, C2Y, C2M |
| | IIR-M | | +C2S, C2L, C2X |
| | IIF | +L5 | +C5I, C5Q, C5X |
| GLONASS | M | L1, L2 | C1C, C1P, C2C, C2P |
| | K | +L3 | +C3I, C3Q, C3X |
| BeiDou | GEO, IGSO, MEO | B1, | C2I, C2Q, X2X |
| | | B2, | C7I, C7Q, C7X |
| | | B3 | C6I, C6Q, C6X |
| Galileo | IOV, FOC | E1, | C1A, C1B, C1C, C1X, C1Z |
| | | E5a, | C5I, C5Q, C5X |
| | | E5b, | C7I, C7Q, C7X |
| | | E5(E5a+E5b), | C8I, C8Q, C8X |
| | | E6 | C6A, C6B, C6C, C6X, C6Z |
| QZSS | IGSO | L1, | C1C, C1S, C1L, C1X, C1Z |
| | | L2, | C2S, C2L, C2X |
| | | L5, | C5I, C5Q, C5X |
| | | LEX | C6S, C6L, C6X |
| IRNSS | IGSO | L5, | C5A, C5B, C5C, C5X |
| | | S | C9A, C9B, C9C, C9X |

*(overview of the available GNSS with their frequencies and signal tracking modes)*

### Emerging questions:

In particular for the clock combination:
- How to consider the potential biases if each AC shall be free to choose any of the frequencies, signals and available observation types.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## CODE and ESA IGS orbit products comparison

As a first step we compared the IGS final solutions from CODE and ESA , which are both generated to provide fully consistent GPS and GLONASS orbit products. This setup allows to get a first answer to the question to which extent the noisier orbit from GLONASS degrades the better GPS orbit in a combined combination scheme.

For this purpose we consider three different schemes to compare the two orbit products:
(1) extracting only the GPS satellites,
(2) considering only the GLONASS satelilites,
(3) taking all GPS and GLONASS satelites into account.

The comparison includes the 7-Helmert transformation parameters (scale, 3 rotation and 3 translation parameters) between the two set of orbits, one being CODE solution and the other one ESA solution. The table below shows the mean values and standard deviations of Helmert transformation parameters estimated from the orbit comparisons of one week.

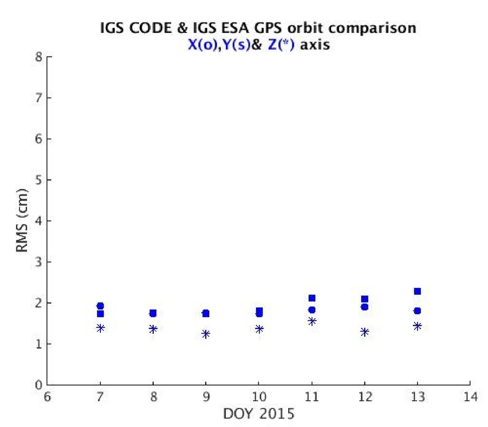
| | GPS-only | | GLONASS-only | | GPS+GLONASS | |
|---|---|---|---|---|---|---|
| | mean | std-dev. | mean | std-dev. | mean | std-dev. |
| **Scale** | **0.23 ppb** | **0.05 ppb** | **0.35 ppb** | **0.10 ppb** | **0.28 ppb** | **0.07 ppb** |
| Rotation x | 0.04 mas | 0.02 mas | 0.04 mas | 0.03 mas | 0.04 mas | 0.02 mas |
| Rotation y | 0.01 mas | 0.01 mas | 0.06 mas | 0.02 mas | 0.03 mas | 0.02 mas |
| Rotation z | 0.04 mas | 0.02 mas | 0.08 mas | 0.03 mas | 0.02 mas | 0.01 mas |
| Translation x | -0.2 mm | 0.5 mm | -1.1 mm | 1.6 mm | -0.1 mm | 0.8 mm |
| Translation y | 2.1 mm | 0.7 mm | -1.1 mm | 1.1 mm | 0.7 mm | 0.4 mm |
| **Translation z** | **-7.1 mm** | **2.8 mm** | **21.7 mm** | **3.7 mm** | 5.5 mm | 2.8 mm |

*(Transformation parameters when comparing the CODE and ESA contributions to the IGS final product during one week in January 2015 considering a subset or even all satellites; the values exceeding 3 times the standard deviation are indicated.)*

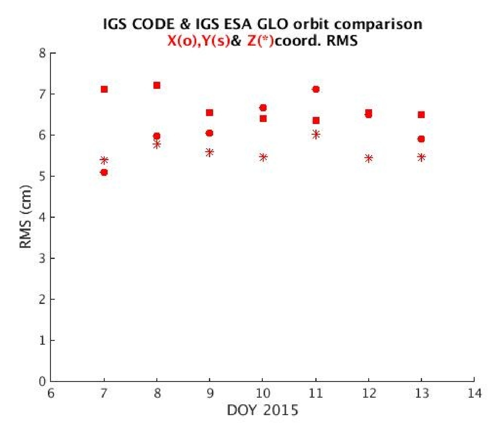
The scale and the translations in the z direction are the two parameters where the two solutions show significant differences. The scale differences between the GPS-only and GLONASS-only comparison is about 0.1 ppb which corresponds to about 2.5 cm in the radial component at the height of the GPS and GLONASS satellites. In addition, the CODE and ESA GLO-only orbit products differ by about 3 cm in the z translation.

Both discrepancies are reflected in the differences between the transformation parameters obtained by the single-system and the GPS+GLONASS approach. This is reflected in a degradation of the residuals, which affects the RMS after applying the transformation parameters to the orbit comparisons. The corresponding plots for GPS-only (1), GLONASS-only (2) and GPS+ GLONASS (3, where the RMS for the GPS and GLONASS satellites are computed separately to make it comparable to the single system cases) are shown below.

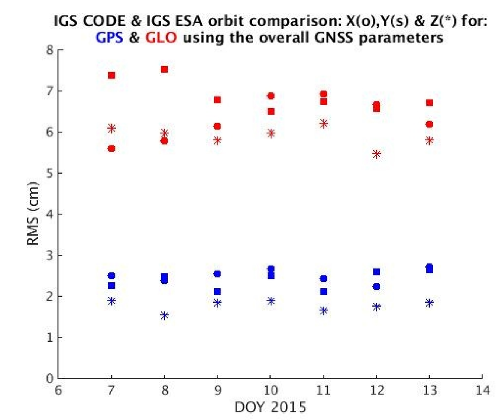
1




2




3




As expected, the RMS of the orbit comparison increases by ~25% for the GPS and by ~9% for the GLONASS satellites, when applying the transformation parameters obtained from both GPS and GLONASS instead of separately derived ones.
**With the current combination scheme both AC's would be «punished» by a reduction of their weight to the combined product when they are submitting multi-GNSS instead of single system contributions.**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## Next steps

In the table of Helmert parameters from the orbit comparison the scale and the translation in the Z direction were significantly different between the GPS- and GLONASS-only satellites. Both components differences are typically related to differences in the processing schemes between AC's. It is noticable that they also appear because CODE as well as ESA follow an approach of a rigorously combined processing of GPS and GLONASS observations. It seems to be essential at this point, to understand the differences in the processing schemes of the two IGS analysis centers and their impact on the GPS and GLONASS satellites to derive a new, multi-GNSS capable combination scheme for the orbit products.

For this matter, we compared and analyzed the two IGS standard processing schemes from CODE and ESA in the table below. In addition a common reference scheme was developed for both software packages BSW and NAPEOS in order to create an impact matrix to improve the understanding of different effects on the GPS and GLONASS orbits and to derive the necessary degrees of freedom for a new multi-GNSS capable orbit combination scheme.

| | CODE IGS final processing | BSW Reference scheme | ESA IGS final processing | Napeos Reference scheme |
|---|---|---|---|---|
| **Measurement Models** | | | | |
| GNSS | GPS, GLO | GPS,GLO | GPS, GLO | GPS,GLO |
| Observable Type | Double difference | Double difference | Undifference | Undifference |
| Orbit+Clock data Rate | 3 min | 5 min | 5 min; 30 sec | 5 min |
| Elevation Cutoff | 3 deg | 5 deg | 10 deg | 5 deg |
| **Terrestrial Reference Frame** | | | | |
| IGb08 for frame alignments? | submit NEQ | Common list station | submit NEQ | Common list station |
| Orbits consistency | IGb08 | NNR on IGb08 core sites | NNR on IGb08 | NNR on IGb08 core sites |
| Clocks consistency | IGb08 | IGb08 | NNR+NNT on IGb08 | NNR on IGb08 |
| **Satellite Dynamics&Inertial Frame** | | | | |
| Subdaily EOP tide model | IERS 2010 | IERS 2010 | IERS 2010 | IERS 2010 |
| SRP Params (& constraints) | D,Y,X scales + X 1/rev; no constraints; Estimation of 5 parameters | No a priori Box-wing model; 5 parameters for SRP and NO stochastic pulses | Box-wing model for apriori modeling of the Solar Radiation Pressure Forces D,Y,B scales + B 1/rev; no constraints | No a priori Box-wing model; 5 parameters for SRP |
| GPS eclipse attitude | nominal | nominal | nominal | nominal |
| GLO SV Attitude for Eclipses | nominal | nominal | yaw rates applied (Dilsner, 2010) | nominal (no yaw rates) |
| **Geopotential** | | | | |
| Static Gravity Field | EGM2008 (12x12) | EIGEN-GLO4C | EIGEN-GL05C (12x12) | EIGEN-GLO05C |
| Low-degree time variations | IERS 2010 | IERS 2010 | None | None |
| **Displacements at Stations** | | | | |
| Solid Earth, Ocean Pole & Loading | IERS 2010 | IERS 2010 | IERS 2010 | IERS 2010 |
| Atmospheric S1/S2 | IERS 2010 | IERS 2010 | none | none |
| Atmospheric Pressure Loading | none | none | none | none |
| **Tropospheric Delay** | | | | |
| Model | VMF1 | GPT | GPT | GPT |
| a priori zenith delay | ECMWF-based ZDD | Saastamoinen model | Saastamoinen model | Saastamoinen model |
| Mapping function used for ZD? | VMF1_HT wet mapping function | GMF wet mapping function | GMF wet mapping function | GMF wet mapping function |
| **Ionospheric Delay** | | | | |
| 1st-order effect | eliminated L1/L2 linear comb. | eliminated L1/L2 linear comb. | eliminated L1/L2 linear comb. | eliminated L1/L2 linear comb. |
| **Estimated Parameters** | | | | |
| Station coordinates | Adjusted with minimum constraints | Adjusted with minimum constraints | Adjusted relative to a priori values from IGS RF | Adjusted relative to a priori values from IGS RF (NNR) |
| Satellite & Receiver clocks | Elimination in DD processing | Estimated in CLOCKFINAL.BPE | 30 sec rate | 30 sec |
| Orbits | 6 Keplerian elements + 5 solar radiation parameters (Constants in D-, Y- and X-direction; Periodic terms in X-direction); no a priori sigmas. Pseudo-stochastic orbit parameters (small velocity changes) | As for IGS processing (3 day arc solution) except: NO STOCH. PULSES | Deterministic positions and velocities; parameters from the Enhanced CODE orbit model (Springer 1999): D0, Y0, B0, Bcos(u) and Bsin(u) In addition we allow for small along-track accel. A0, Acos(u), Asin(u) | As for IGS processing except: NO ALONG-TRACK ACCELERATION |
| Troposphere zenith delay | Linear parameters every 2 hours | Linear parameters every 2 hours | Linear parameters every 1 hour | Linear parameters every 2 hours |
| Ambiguity fixing | Baseline-by-baseline mode - Melbourne-Wuebbena (< 6000 km) - Quasi-Ionosphere-Free (QIF) approach (< 2000 km) - Phase-based widelane(< 200 km) - Direct L1/L2 method | As for IGS processing except: NOT AMB FIX FOR GLO | Phase cycle ambiguities adjusted except when double-difference ambiguities can be resolved confidently; integer ambiguity resolution scheme from GFZ | As for IGS processing |
| Earth orientation parameters(EOP) | Daily x & y pole offsets, pole-rates, UT1, LOD | Daily x & y pole offsets, pole-rates, UT1, LOD | Daily x & y pole offsets, pole-rates, UT1, LOD | Daily x & y pole offsets, pole-rates, UT1, LOD |
| Intersystem biases | GPS <-> GLONASS biases | (GPS <-> GLO biases) per satellite | GPS <-> GLONASS biases | (GPS <-> GLO biases) per satellite |

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